Paleocollapse structure as a passageway for groundwater flow and contaminant transport

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Abstract Paleocollapse structure is a rock collapse, resulting from the failure in the geological history of the bedrock overlying karstified limestone. Depending on the present hydrogeological conditions within the area of paleocollapse and the internal properties of these structures, they can provide a means to facilitate groundwater flow and contaminant transport. Inactive paleocollapse structures can be reactivated by human activities such as dam construction, mining underground minerals, pumping groundwater, and development of landfills. They can also be reactivated by natural events such as earthquakes and neotectonic movements. In the mines of northern China, sudden inflow of karst water from Ordovician limestone into drifts and mining stopes through paleocollapse structures has caused significant economic loss. Water pumping tests and accompanied dye traces are effective approaches of locating water-conducting paleocollapse structures. Grouting is probably the best means of preventing them from becoming geohazards.

Key words Paleocollapse · Karst · Groundwater flow · Contamination

Introduction

Collapse structures could be classified into many types based on differences in host rocks, origin, and history of development. Two basic types are sediment collapses, also known as cover collapses and rock collapses (Newton 1987). For slow processes, they are called cover subsidence and rock subsidence, respectively. Research of historical records shows that most collapses are cover collapses, leading to sinkholes (Beck 1991), where unconsolidated sediments overlying carbonate bedrock move downward through dissolution openings into a network of dissolved void space or a single large cavity, capable of accommodating the sediments. In recent years, the cover collapse sinkholes have been extensively studied and well documented due to their recognized sensitivity to human activities and their impacts on engineering works and the environment (Newton 1987; Beck 1984; Beck and Wilson 1987).

The occurrence of bedrock collapses is rare compared with that of cover collapse sinkholes (Newton 1987). Most of the human-induced rock collapses are related to dam construction in mountainous areas, where water potential differences between recharge and discharge zones are great (Yuan 1987). Continuous and repeated change in air and water pressure (the hammer effects) in karst conduits are the main factors triggering rock collapses (Fig. 1). In southern China, over 20% of reservoirs built in areas of bare karst failed to retain water due to the rock collapses at their bottoms (Zou 1994). Rock collapse dolines are rarely seen in the act of collapsing (White 1988). None of the 1700 sinkholes which have occurred in

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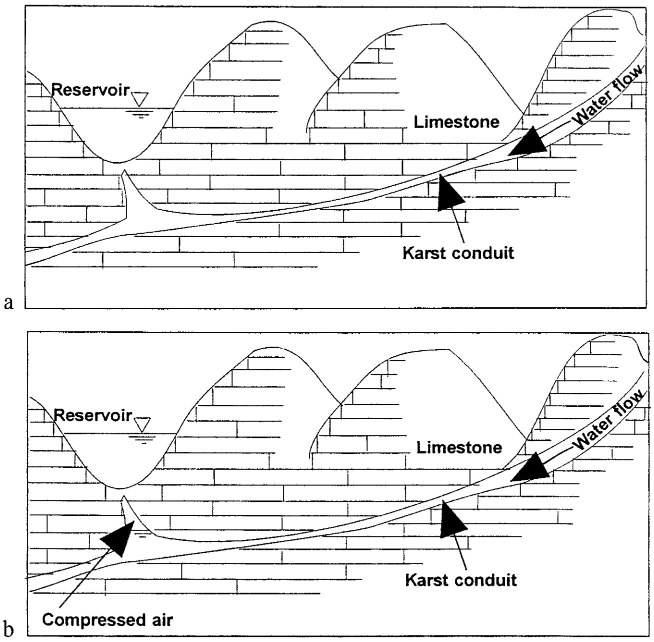

Fig. 1a,b
Illustration of rock collapses in karst reservoirs. **a** Due to water explosion; **b** due to air explosion

Florida, United States during the past 25 years has been confirmed as cave roof collapse (Beck 1991). However, these sinkholes are newly developed; on a geologic timescale, cave-roof collapses are possible (Waltham 1989) and widely distributed as well (Sangster 1988; Li and Zhou 1989; Vegter and Foster 1992). Rock collapses developed in the past geological history are referred to as paleocollapse structures or paleocollapse breccia pipes. Depending on present hydrogeological conditions within areas of paleocollapses and the internal properties of these structures, they can function as a weak geological medium to facilitate groundwater flow and contaminant transport (Benson and others 1991). Inactive paleocollapse structures can be reactivated by human activities such as dam construction, mining underground minerals, pumping groundwater, and development of landfills. They may also be reactivated by natural events such as earthquakes and neotectonic activities.

Paleocollapses and their hazards

Geology and climate are two major factors affecting the development of karst features. Usually, there have been several phases of karstification during geological history. In China, for example, the most striking paleokarst is found in (1) the Caledonian Orogeny unconformity between the Ordovician limestone and middle carboniferous series in northern China, (2) the unconformity between the Lower Permian limestone and the Upper Permian Series in southern China, (3) the pre-Jurassic karstification in the Sichuan basin, and (4) the pre-Tertiary buried karst in northern China. The effects of paleokarst can be observed in the various karst features of the carbonate aquifers and the yields of the oil and gas reservoir. They can also be seen in the interrelationships between important mineral deposits and karst aquifers which pose difficult problems in mining engineering. Paleocollapse structures are one of the most important types of paleokarst features.

Paleocollapse structures are widely distributed in northern China, especially in the provinces of Shanxi and Hebei, as listed in Table 1. They have been found in over 20 coalfields and their total number exceeds 3000 with a intensity of up to 70 km^2. In some stopes paleocollapse structures comprise 30% of the total mined areas. They are recognizable in plane view as patches of breccia with miscellaneous lithological composition, generally derived from overlying strata and completely enclosed in lower bedrock. Diameters range from tens to hundreds of meters with the largest measuring 1050 m. In profile, they

Table 1
Paleocollapse structures found in northern China's coalfields

Province	location	no. of collapses	max. size of collapses (m)			water inrush
			length	width	height	
Shaanxi	Xishan Mine, Taiyuan	1300	40			
	Yangquan Mine	960	300		600	
	Huoxian Mine	405	60			2
	Zhuangjiazhuang Mine, Fenxi	360	30			1
	Shenlin Mine	75	30			
Hebei	Jingxing Mine	112	300	23	300	1
	Fenfeng Mine no. 1	6	200	40		
	Fengfeng Mine no. 4	20	73	150		
	Yangquhe Mine	6	204	57		
	Fangezhuang Mine, Kailuan	9	95	74	280	4
	Tangjiazhuang Mine, Kailuan	5	116		50	
Henan	Hebi Mine	22	200	60	398	
	Tongyie Mine, Anyang	22				1
	Lifeng Mine, Jiaozuo	1				1
Jiangsu	Dahuangsha Shaft, Xuzhou	17	200	146		1
	Qingshanzong Shaft No. 1	1				1
	Qingzhuan Mine	1	38	19		
	Liuxing Mine	1		20		
	Jincheng Mine	27	125	62		
	Xinhe Mine	3	136	100		
	Jiahe Mine	1	135	100		1
	Wangzhuang Mine	1	122	93		
	Quanzhao Mine	7	60	40		
	Hanqiao Mine	4	170	100		
	Dongzhuang Mine	1	280	200		
	Yian Mine	1				

take the form of vertical cylinders several hundred meters deep. No bedding is apparent inside these structures and the different rocks are intermixed and poorly sorted.

They generally contain higher proportions of displaced blocks and the adjoining strata are offset as a result of dissolution-collapse. Fragments tend to be sharply angular, typically rotated, show little sign of wear and have dropped from their original stratigraphic position.

The origin of this type of collapse is not fully understood, but the bottom of a paleocollapse structure is usually in the underlying karstified Ordovician limestone, and the lithological character of the breccia gives a strong impression of collapse of upper strata. Gypsum in the Ordovician limestone is recognized as playing an important role in paleocollapse formation, as its volume expands significantly on contact with water, forming fractures or cavities in the limestone (Li and Zhou 1990). After the gypsum dissolved and was removed by groundwater, numerous cavities or fractures were left behind. Solution of the gypsum layers and continuous dissolution of the limestone eventually led to the collapse of the overlying strata. Development of a paleocollapse is envisaged as a more or less continuous process which progresses upward from an initial conduit (cave) until an equilibrium pressure arch configuration is attained. This occurs when a collapse reaches a lithologic unit of sufficient strength, or the cavity is completely filled with breccia and thus becomes self-supporting.

Usually the infill materials in paleocollapse structures are tabular 5–40 cm angular fragments which display random orientation. Sides are subparallel and contacts between host and fills are sharp and irregular. In most cases, the matrix is a classic sediments without cement or mineralization (Fig. 2). Due to gravity, these structures are generally perpendicular to the ground surface. However, they may become inclined as a result of tectonic movements but remain perpendicular to the surrounding strata.

Voids may be present at the top of the structures and drill bits can drop noticeably during borehole sinking. Closed depressions sometimes form in the surficial sediments without any apparent fluctuation in water level or any construction works taking place. The paleocollapse structures may become impermeable to water when the filling materials were cemented and mineralized.

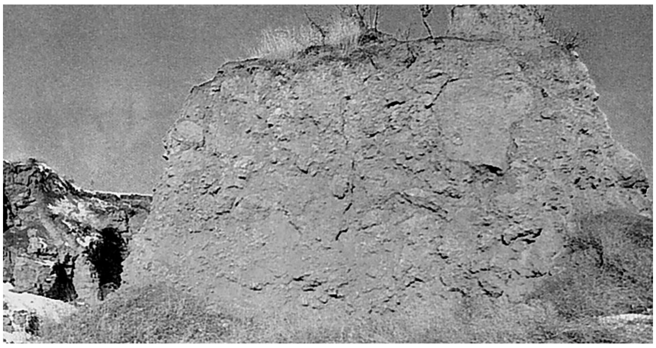

Fig. 2
Filling materials in a paleocollapse structure which were left behind after surrounding Ordovician limestone was quarried

The absence of coal seams and the sudden inrush of karst water from the Ordovician limestone have been encountered in the mines of the Permo-Carboniferous coalfields of northern China. These events are due to the presence of paleocollapse structures; 13 water inrushes have been reported from the mines, including the largest inrush in the world, which occurred in Fangezhuang Mine in 1984 (Table 2). Karst water gushed into the mine at a flow rate of 2048 $m^3\ min^{-1}$ at a depth of 313 m below sea level (bsl). The surface level is 27 m above sea level (asl). The whole mine was flooded within 21 h and as a result the regional water table in the Ordovician limestone dropped from 5.94 m asl to 111.09 m bsl. The cone of water depression covered 84 km^2 with a north-south axis of 25 km.

The fall in the level of the water table in the Ordovician limestone caused serious problems for local residents. These included the drying up of their water supply wells, contamination of the groundwater and the formation of new sinkholes. The water inrush led to the development of 17 cover collapses, with resulting sinkholes ranging in diameter from 2.5 to 3 m and with depths of 3 to 12 m.

Three basic conditions are required to cause a water inrush. These are the presence of:

1. water-bearing karst conduits or a nearby water body;
2. water-permeable internal structures in the paleocollapses;
3. a water pressure difference between the karst aquifer and the working area.

The relative location of a mine to the active flow zone or karst conduits in karst aquifers determines the amount of water that can flow into the mine. In the presence of a large water-pressure difference, hydrofracturing will facilitate the upward flow of Ordovician karst water into mines. Apparently inactive paleocollapse structures or those which have been cemented can be reactivated by activities such as mining, pumping water, dam construction, and landfill development. They may also be triggered by natural events such as neotectonic movements and earthquakes. Table 2 provides some examples and Fig. 3 shows three scenarios where paleocollapse structures can lead to water inrushes.

Mining drifts do not have to intercept paleocollapse structures directly to cause a geohazards but may instead intercept faults or fractures connected to them. However, once a water inrush occurs and significant water flows into the workings, the whole mine or quarry may become flooded. In cases where different aquifers, several hundred meters apart, become hydraulically connected, contaminated water may degrade water of previously good quality. The landfill closure and landfill site selection tends to be more complicated when paleocollapse structures are involved (Benson and others 1991).

Table 2
Case histories of karst water inrushes through paleocollapse structures in northern China

Mine	date	flow rate (m^3/min)	description	hazard
Tongyie Mine, Anyuang	1965	23.3	A water inspection borehole drilled into a paleocollapse structure from a drift. The initial water flow rate was 0.5 m^3 min^{-1} and water flow rate increased to 23.3 m^3 min^{-1}. An exploration borehole revealed 17 cavities within 50 m of the collapse with the maximum bit-drop of 2.59 m	The whole mine was flooded
Lifeng Mine, Jiaozuo	1967	120	Karst developed very well in the area. Intensive mine water drainage reactivated the paleocollapse structure	A working stope was flooded
Fagezhuang Mine, Kailuan	1978	59.7	Water flowed into the mine from the sandstone, which is 160 m above the underlying Ordovician limestone. A sluice gate was constructed to isolate the water inflow area and a 0.2-m fracture was revealed, connected with a paleocollapse structure	Part of a drift and a working stope (70188 m^3) was flooded
Fagezhuang Mine, Kailuan	1983	14	A small fault with displacement of 0.2–0.5 m was intercepted by a working stope. Karst water flowed through a paleocollapse structure into the fault and then to the working stope	The working stope was flooded
Fagezhuang Mine, Kailuan	1984	2053	This is the biggest water inflow incident in the world. The mining coal seam was 180 m above the Ordovician limestone but they are connected by a paleocollapse structure. The reactivation of the paleocollapse may be associated with a recent earthquake in this area. Grouting boreholes revealed that the top of the sinkhole was unfilled with sediments. Due to the water inrush, 17 cover sinkholes were induced on the surface	The whole mine was flooded and the adjacent three mines were treathened
Huoxian Mine	1967	7.8	Karst water flowed into an excavating drift through a paleocollapse structure and a connecting fault	The drift was abandoned
Huaxian Mine	1984	3.3	Karst water from a paleocollapse structure flowed into surrounding fractures and then into the horizontal drift in the Ordovician limestone	

Detection and remediation of hazardous paleocollapse structures

Because the impacts of paleocollapse structures on the environment and engineering works are serious, it is essential to locate their positions before they are actually exposed. A variety of methods, including geophysical and geochemical ones, are used; exactly which depends on site conditions. In northern China, a combination of pumping tests and dye-tracing tests proved effective in locating two paleocollapse structures in Fengfeng Mine No.4.

The major geological strata in Fengfeng Mine No.4 is shown in Fig. 4. The Carboniferous thin-bedded limestone (Daqing limestone) and the Ordovician limestone are the two major aquifers. The average thickness of the Daqing aquifer is some 5.5 m. Sixty-nine per cent of the boreholes sunk in this aquifer, within the mining area, discharge over 1 m^3 min^{-1} with the maximum discharge of 15 m^3 min^{-1}. Forty days' continuous pumping at 41 m^3 min^{-1} did not drain the aquifer, instead, its piezometric pressure remained stable. Observation wells in the Ordovician limestone recorded a drop in piezometric level. Therefore, it was concluded that the Daqing aquifer was receiving water from the Ordovician limestone aquifer and subsequent analyses indicated both aquifers to have the same chemistry. Geologic structure analysis and exploratory drilling suggested that lateral inflow from outside the mine was impossible due to impervious faults (Fig. 5). Thus, the connecting link between the two aquifers must be vertical. Paleocollapse structures are one possible explanation for this, and indeed over twenty such structures have been intersected in the mined area. Surface geophysical methods were unsuccessful in locating the paleocollapse structures due to the big depths involved (Li and Zhou 1990). However, the well logs indicated that boreholes at positions A and B in Fig. 5 strongly adsorbed electric-magnetic waves.

Pumping test results together with dye tracing confirmed the findings by the well-logs and enabled the paleocollapse structures to be located. Four pumping tests were conducted in the Daqing aquifer at the rates of 11.9, 25, 20 and 26.4 m^3 min^{-1}, respectively. Piezometric pressures in both aquifers showed corresponding fluctuations. The pumping in the Daqing aquifer caused a cone of depression in the Ordovician limestone. During each pumping test, a conservative fluorescent dye was introduced into a borehole in the Ordovician limestone and was collected at all accessible boreholes and discharge points in the Daqing aquifer. The results of the dye tracing are shown in Fig. 5. In all cases, the dye first appeared in boreholes

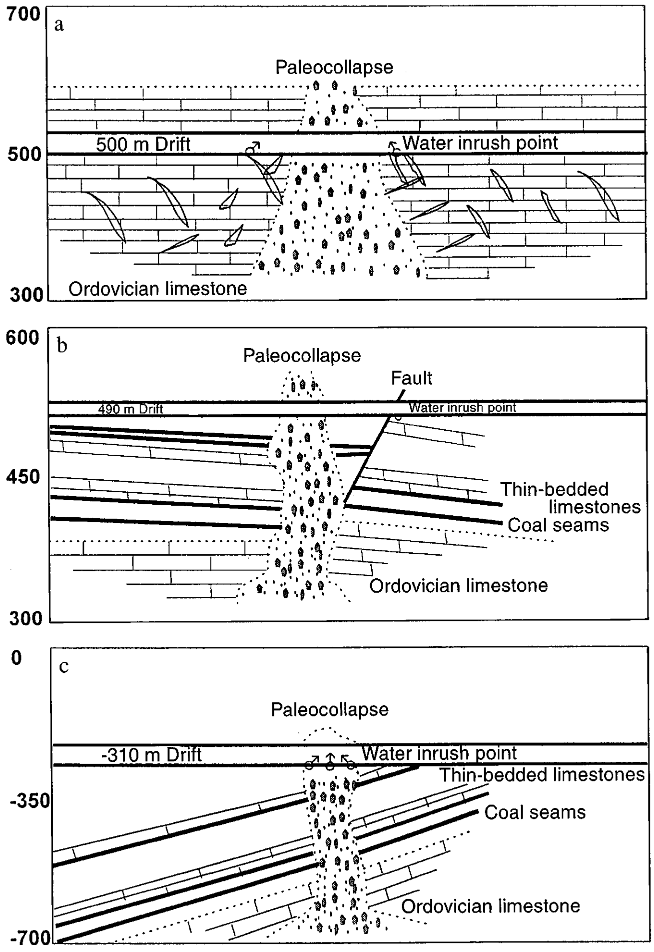

Fig. 3a–c
Scenarios where karst water from Ordovician limestone flows into workings through paleocollapse structures. **a** Through paleocollapse-connected fissures; **b** through paleocollapse-connected faults; **c** through paleocollapses

in areas A and B. The straight-line velocities were calculated based on the distances and the dye travel times. Dye traces 1, 2, 3, and 4 had velocities to area A of 0.62, 0.43, 0.08, and 6.5 m^3 min^{-1}, respectively; and to area B of 0.39, 0.52, 0.1, and 11.4 m^3 min^{-1}, respectively. The high but contrasting velocities from different traces highlight the rapid flow and strong heterogeneity in the Ordovician limestone aquifer. This in turn assisted in delineation of the possible locations of water-conducting paleocollapse structures. Subsequently, 16 grouted boreholes were drilled into the suspected paleocollapse structures and the adjoining Daqing aquifer so as to seal-off and plug the vertical passageways (Fig. 6). As a result, the amount of water flowing into the mine decreased from 41 to 3 m^3 min^{-1}, and the piezometric pressure in the Daqing aquifer dropped significantly, as shown in Fig. 7. The investment into the grouting operation was recovered from the savings in dewatering cost within 8 months.

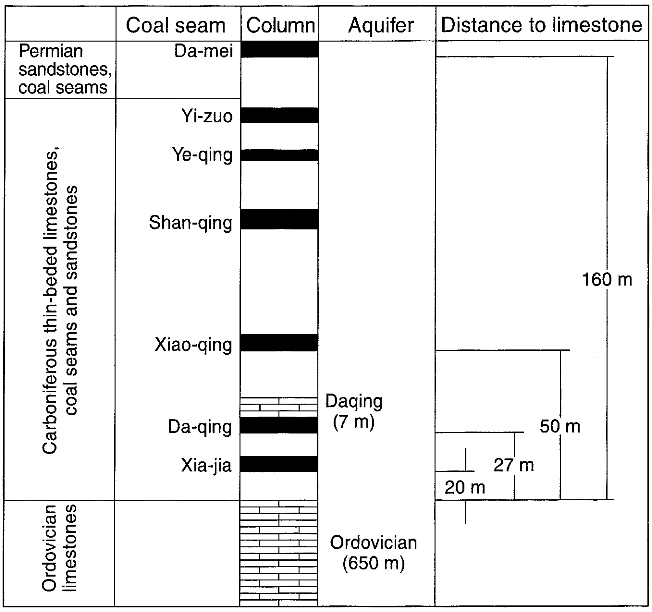

Fig. 4
Geological column in Fengfeng Mine No.4

Conclusions

Paleocollapse structures are common karst features when viewed on a geologic time-scale. They can act as passageway for groundwater flow and contaminant transport. In northern China, significant damage has been caused in mines as a result of these structures, including the largest water inrush in mining history. Three factors determine whether a paleocollapse structure will become a water passageway and thus a geohazard:

1. the paleocollapse structure intercepts water-bearing strata;
2. the water table in the water-bearing strata is higher than the bottom of the mine working;
3. the internal structure of the paleocollapse favors water flow.

The presence of paleocollapse structures indicates a strong groundwater flow (conduit flow) in the areas in the past and does not necessarily reflect present hydrogeological conditions. Only those paleocollapse structures that occur within present conduit flow zones or in the vicinity of a water body have the potential to cause geohazards. Paleocollapse structures may be reactivated by human activities such as dam construction, landfill development, mining and quarrying, intensive water pumping, as well as natural events such as earthquakes or neotectonic movements. A multidisciplinary approach including geophysical prospecting, geochemical analyses, test drilling, pumping tests, and dye tracing is required to locate these structures. Grouting is the most effective and perhaps the only possible way of preventing paleocollapse structures from becoming geohazards. Since grouting is expensive, a cost benefit analysis should be undertaken beforehand.

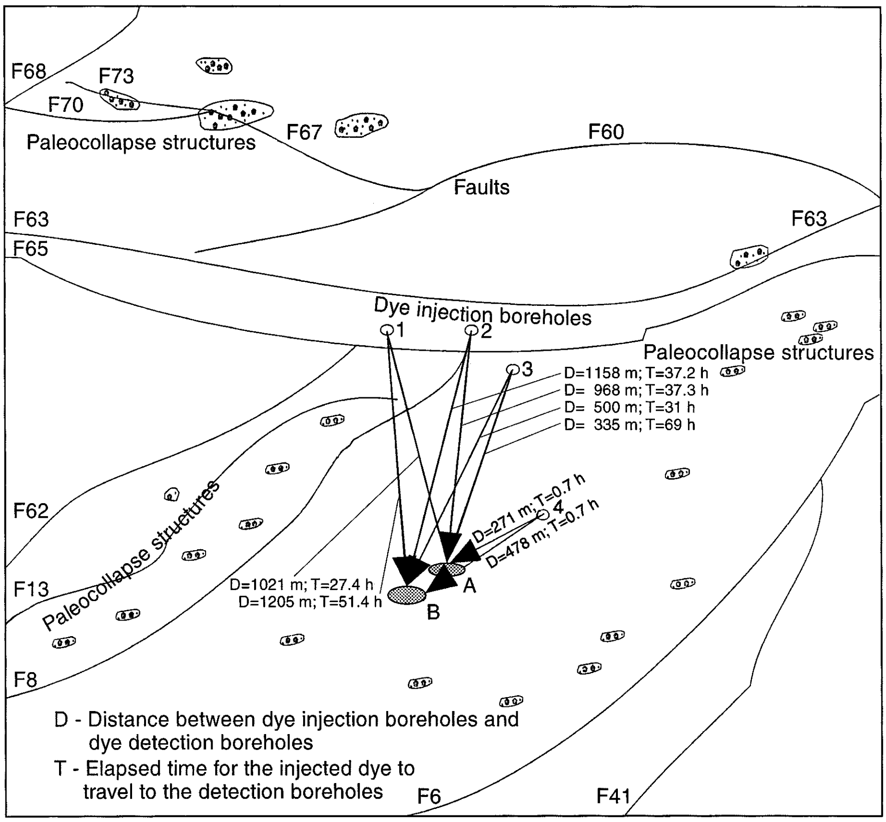

Fig. 5
Locating paleocollapse structures by dye tracing in Fengfeng Mine No.4

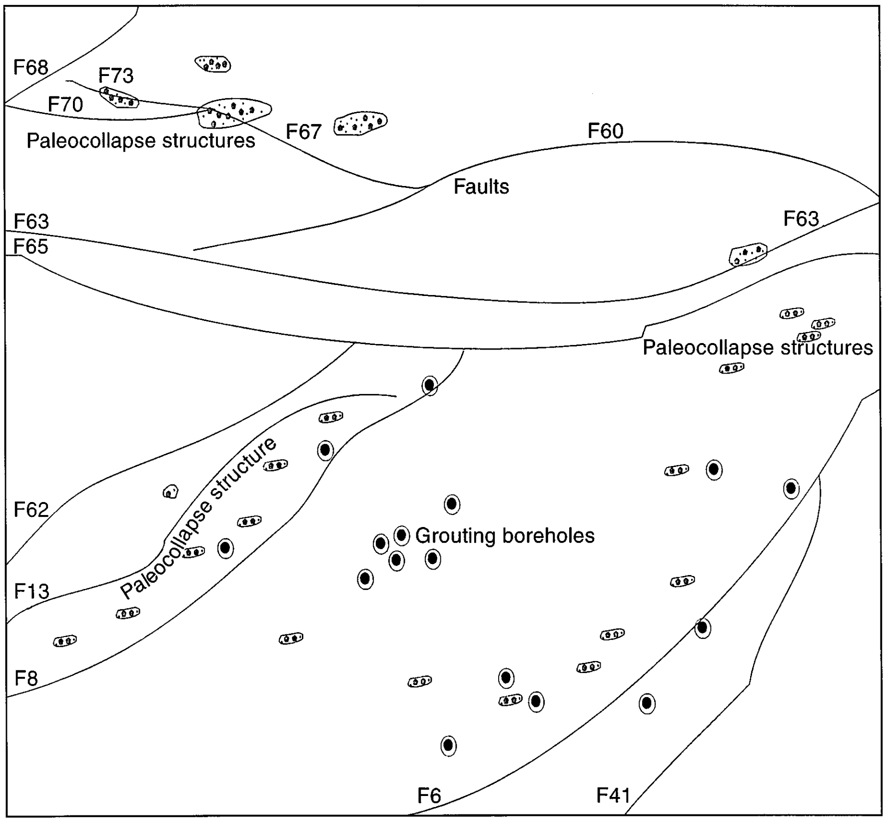

Fig. 6
Distribution of grouted boreholes in Fengfeng Mine No.4

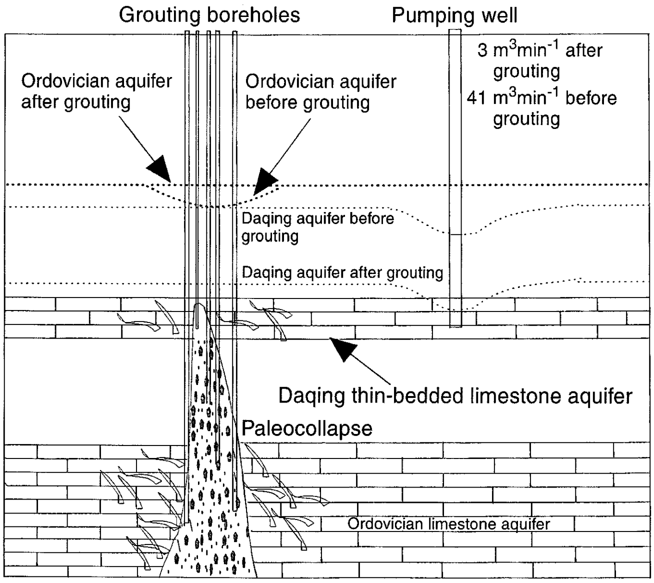

Fig. 7
Plugging the paleocollapse structures by grouting to prevent water inrush in Fengfeng Mine No.4

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